Shake Map Methodology for Intermediate-Depth Vrancea (Romania) Earthquakes

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We establish and test a shake map methodology for intermediate-depth Vrancea earthquakes, based on seismological information gathered in Romania during recent years. We use region- (azimuth-) dependent attenuation relations derived from stochastic simulations of ground motions using spectral models of Vrancea earthquakes. Both region boundaries and Fourier amplification spectra for the characterization of seismic site effects are based on several hundred weak, moderate and strong-motion records and macroseismic intensity maps. We determine region-specific, magnitude- and distance-dependent amplification factors of peak values and instrumental intensity relative to rock. We interpolate recorded ground motions and ground motion estimates from the obtained amplification factors and attenuation relations for rock conditions. The resulting shake maps show a good agreement with macroseismic descriptions of moderate-sized and large Vrancea earthquakes, demonstrating the feasibility of a seismological approach to shake map generation. Unlike previous methodologies, this approach requires neither expensive assessments of geology-dependent site amplification factors, nor large numbers of strong-motion records. Our results are in good agreement with empirical topographic slope-site amplification relations, but give a better reflection of the abnormal attenuation of seismic waves in the Transylvanian region and the strong amplification in the Focsani basin.
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INTRODUCTION

Shake maps depict the level and distribution of seismic ground shaking caused by a real or scenario earthquake. This information is essential for the (1) emergency response and loss estimation in the aftermath of strong earthquakes (if provided in near real-time), (2) public information and education, (3) earthquake engineering and seismological research, and (4) the planning and training of task forces and stakeholders (Wald et al. 2005).

In most earthquake-prone regions in the world, coverage with seismic sensors is poor and strategies for a stable spatial interpolation of recorded ground motions for the generation of shake maps are required. To increase the density of required nodes for interpolation, the well-known ShakeMap, initially developed for earthquakes in California (Wald et al. 1999), integrates estimated seismic ground shaking at a grid of *phantom*

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stations in sparsely covered areas. Ground motions at these sites are estimated from empirical attenuation relations and geology-dependent amplification factors for different soil types (Wald et al. 1999).

Amplification factors used for ShakeMap were empirically determined by Park and Ellrick (1998), who linked frequency- and amplitude-dependent amplification values for different shear-wave velocities in the subsurface layers (Borcherdt 1994) to Quaternary, Tertiary, and Mesozoic geologic units, corresponding to soil, soft rock, and hardrock conditions, respectively (Wald et al. 1999). This procedure requires both expensive geological and geotechnical data, as well as large numbers of ground motion records in regions, in which ShakeMap shall be established.

Recently, Wald and Allen (2007) proposed to derive first-order amplification maps from topographic data. The authors correlated shear-wave velocity data averaged down to 30 m (V_{S30}) from the United States, Taiwan, Italy, and Australia with the topographic slope in active tectonic regions and stable shields. They found that the use of topographic slopes and their empirically assigned V_{S30} values provide a simple approach to a uniform site-condition mapping which might be usable for shake map generation, e.g., within the Prompt Assessment of Global Earthquakes for Response (PAGER) program of the U.S. Geological Survey National Earthquake Information Center (Wald et al. 2006).

Using the example of Romania, in this paper, we will present an alternative shake map methodology that does not require empirical relationships between geologic units (as documented in geological maps) and site amplification, but rather, one that is based on seismological information. We will compare our results with outcomes of the empirical topographic slope and amplification approach by Wald and Allen (2007).

The Romanian Kinemetrics K2 strong motion network with about 40 accelerometers covering mainly the southeastern part of the country (Bonjer et al. 2000) provides the required observational component for shake maps in Romania. The installation of the network started in 1996 in joint efforts of the National Institute for Earth Physics (NIEP) in Bucharest, Romania, and the Collaborative Research Center 461: Strong Earthquakes—A Challenge for Geosciences and Civil Engineering (http://www-sfb461.ipf.uni-karlsruhe.de/) at Karlsruhe University, Germany.

The installation of the strong motion network started after Romania was hit by four large earthquakes during the last century: on November 10, 1940 (moment magnitude, M_w, $=7.7$), March 4, 1977 ($M_w=7.4$), August 30, 1986 ($M_w=7.1$), and May 30, 1990 ($M_w=6.9$) (Oncescu et al. 1999). The 1977 event was most damaging and caused 1,570 fatalities, more than 11,300 injured people—90% of them in the Romanian capital Bucharest, and USD 2 billion direct damage costs (Sandi 2001, Georgescu and Pomonis 2007). There exists only a small number of strong-motion recordings of these events due to a poor seismic instrumentation in Romania during this time. The 1977 earthquake, for example, was recorded at only one single site in Bucharest, around 200 km southwest of the epicenter.

All strong earthquakes and many small- to moderate-sized events in Romania occurred at depths between 70 km and 180 km in the well-defined seismogenic Vrancea zone, southeastern Carpathians. Previous studies based on macroseismic and instrumental data (e.g., Ivan et al. 1998, Mandrescu 1984, Mandrescu and Radulian 1999, Mandrescu et al. 1988, Moldovan et al. 2000, Popa et al. 2005) revealed several peculiarities of intermediate-depth Vrancea earthquakes: (1) they affect very large areas with a predominant northeast-southwest orientation, and (2) site effects from local and regional geology cause a large variability of ground motions in Romania, usually controlling the amplitudes and frequency content of shaking to a larger extent than magnitude and distance. These features make the application of ground motion relations and site characteristics from other regions to Vrancea earthquakes questionable and underline the need of an alternative shake map approach in Romania.

METHOD

Similar to the ShakeMap approach (Wald et al. 1999, 2005), our methodology combines (1) recorded ground motion data, (2) empirical attenuation relationships for rock site condition, and (3) magnitude-dependent amplification maps relative to rock. We determine shake maps for peak ground acceleration (*PGA*), peak ground velocity (*PGV*), and instrumental intensity (*II*). The main steps can be summarized as follows:

- Collection of observed ground motion data from recording stations and extraction of ground motion parameter IM, e.g., PGA
- Determination of moment magnitude, M_w, and hypocentral location
- Estimation of IM on a regular grid of phantom stations using empirical attenuation relations for rock condition
- Correction of IM to rock, based on amplification values at the recording sites
- Interpolation of IM values at the phantom and recording stations (corrected to rock) onto a fine rock grid of 0.01° spacing
- Amplification of IM values at each fine grid point using amplification maps

For the spatial interpolation and plotting of our shake maps we make use of tools provided by the Generic Mapping Tools (GMT, Wessel and Smith 1991). We apply a surface gridding algorithm with continuous-curvature and adjustable tension. The same algorithm and parameters are used in ShakeMap (Wald et al. 1999). We arrange the phantom stations on a regular grid of 45 km spacing covering the Romanian territory. Prior to the interpolation of recorded and estimated ground motions, we remove all phantom sites within a 35 km radius around each recording station.

Similar to what was initially proposed by Sokolov and Wenzel (2007) and refined by Sokolov et al. (2008), we divide the Romanian territory into eight characteristic regions (Figure 1). The region outlining is based on observations of weak and strong ground motions during past Vrancea earthquakes and, to a lesser extent, on geological and geomorphic characteristics (Sokolov et al. 2008). For the shake-map approach, we treat each of the eight zones separately from the others by using region-specific (azimuth-dependent) amplification functions and attenuation relations.

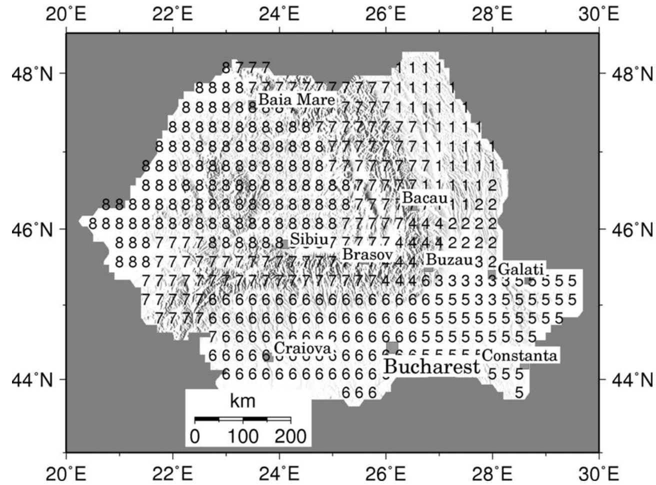

Figure 1. Eight characteristic regions in Romania: (1) North, (2) East, (3) Focsani, (4) Vrancea, (5) South, (6) Southwest, (7) Rock (Mountain), and (8) Transylvania. The region outlining is based on seismological observations during past Vrancea earthquakes and, to lesser extents, on geological and geomorphologic site conditions (Sokolov et al. 2008).

SPECTRAL AMPLIFICATION FUNCTIONS AND ATTENUATION RELATIONS FOR VRANCEA EARTHQUAKES

Site conditions in Romania vary from metamorphic rock to thick and water-saturated sedimentary formations. Sokolov et al. (2004b, 2005) determined spectral amplification functions at various sites in Romania, using several hundred earthquake records of about 100 small magnitude ($M<5.5$) events recorded between 1996 and 2004 at the around 40 stations of the Romanian K2 strong motion network (Bonjer et al. 2000) and at 32 broadband stations temporarily installed in southeastern Romania during the 1999/2000 seismic tomography experiment CALIXTO (e.g., Martin et al. 2006). In addition, the authors used several records of five larger events with $6.0 \leq M_w \leq 7.4$ (Oncescu et al. 1999) and macroseismic intensity maps for the 1940 ($M_w=7.7$), 1977 ($M_w=7.4$), 1986 ($M_w=7.1$), and 1990 ($M_w=6.9$) Vrancea earthquakes (Radu et al. 1987). Two so-called nonreference techniques were used: for low frequencies (<1 Hz), Sokolov et al. (2004b, 2005) applied a modification of the well-known horizontal-to-vertical (H/V) Fourier spectral ratio technique; for higher frequencies they applied the so-called very hard rock (VHR) ratio technique which is based on spectral ratios of earthquake records and simulated data for hypothetical VHR conditions. Nonlinear behavior of soil response during strong excitation was neglected in these studies due to the lack of respective data.

By the averaging of Fourier amplification spectra at sites within each of the eight characteristic regions outlined in Figure 1, Sokolov et al. (2008) determined generalized region-specific amplification functions as displayed in Figure 2. Certain ground motion parameters, in particular *PGA*, may be sensitive to the amplitudes of individual peaks in the amplification spectrum. Averaging site amplification functions over different earth-

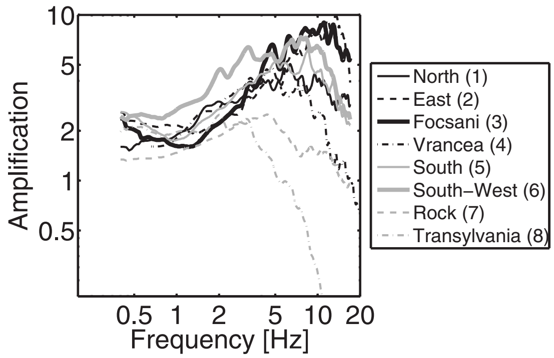

Figure 2. Generalized amplification functions relative to very hard rock for the eight characteristic regions shown in Figure 1. Note that the Transylvanian basin in northwestern Romania (region 8 in Figure 1) is characterized by an anomalous attenuation of seismic waves (Popa et al. 2005, Radulian et al. 2006). The seismic effect of Vrancea earthquakes in this basin is much lower than in other regions for the same distance.

quakes and stations, however, smoothes these peaks and can hence lead to an underestimation of true ground shaking. Recent studies showed that the majority of observed *PGA* values can be reproduced when using the mean and the mean plus one standard deviation of the generalized amplification functions (Sokolov et al. 2004a, b).

Sokolov et al. (2008) combined the generalized amplification functions in Figure 2 with source scaling factors and attenuation models for Vrancea earthquakes (Sokolov et al. 2005) to model ground motion time series for $5.0 \leq M_w \leq 8.0$ at epicentral distances $R < 500$ km applying the stochastic simulation approach (Boore 2003). From the simulated ground motion records, the authors derived empirical attenuation relationships for peak motions *PGA* and *PGV* in each of the eight characteristic regions in Figure 1. For rock site condition, Sokolov et al. (2008) found

$$IM = \exp(a_1 + a_2 \ln(M) - \exp(a_3 + a_4 \ln(H))R + a_5 H + \Delta IM) \tag{1}$$

with source depth H (km) and epicentral distance R (km). For *PGA* (cm/s^2) $a_1 = -8.49907$, $a_2 = 7.73683$, $a_3 = -1.49548$, $a_4 = -0.72045$, and $a_5 = -0.01825$, and for *PGV* (cm/s) it is $a_1 = -15.98974$, $a_2 = 10.52414$, $a_3 = -1.33436$, $a_4 = -0.76610$, and $a_5 = -0.02002$.

From the same dataset, Sokolov et al. (2008) determined attenuation relations for instrumental intensity (MSK scale). They used an empirical method proposed by Chernov and Sokolov (1988) and Sokolov (2002) which relates the amplitudes of the Fourier spectrum of seismic ground motions to levels of seismic intensity. For rock site condition Sokolov et al. (2008) found

$$IM = \exp(a_1 + (a_2 + a_3 H)\ln(M) + (a_4 + a_5\ln(H))R + a_6 H) + \Delta IM. \quad (2)$$

with $a_1 = -1.09700$, $a_2 = 1.78016$, $a_3 = 0.00141$, $a_4 = -0.01213$, $a_5 = 0.00215$, and $a_6 = -0.00762$. The two correction terms ΔIM in Equation 1 and 2 account for the increasing influence of surface waves at increasing distances. As an example, we show in Figure 3 the empirical attenuation relations for *PGA*, *PGV*, and *II* for $5.0 \le M_w \le 8.0$ and source depth $H = 100$ km. For further information see Sokolov et al. (2008).

We determine amplification factors *AMP* from the ratios of ground motions *IM* predicted in the eight regions (using the relations presented in Sokolov et al. 2008) and ground motions predicted for rock site condition IM_{rock} using Equation 1 and 2. These factors depend on moment magnitude M_w, epicentral distance *R*, and source depth *H*, and we thus define

$$AMP(IM, \text{region}, M_w, R, H) \equiv IM(\text{region}, M_w, R, H)/IM_{rock}(M_w, R, H). \quad (3a)$$

For instrumental intensity we define in addition

$$\Delta II(\text{region}, M_w, R, H) \equiv II(\text{region}, M_w, R, H) - II_{rock}(M_w, R, H) \quad (3b)$$

where *II* is the instrumental intensity in each of the eight regions and II_{rock} for rock site condition. Along with the empirical attenuation relations for rock condition in Equation 1 and 2, these amplification factors build the basis for the generation of our shake maps.

RESULTS

AMPLIFICATION FACTORS AND INTENSITY INCREMENTS FOR VRANCEA EARTHQUAKES

As an example, we show in Figure 4 the amplification factors *AMP* and increments ΔII determined from Equation 3a and 3b for the Focsani (left) and the Southwest region (right), corresponding to regions 3 and 6 (Figure 1), respectively. The amplification factors for *PGA* vary between 2.0 and 3.2 (Figure 4a), for *PGV* between 1.6 and 2.3 (Figure 4c), and between 5.0 and 9.0 if we consider the mean plus one standard deviation of *PGA* (Figure 4b). The amplification of instrumental intensity *II* varies between 1.1 and 1.9 (Figure 4d), the intensity increments ΔII range between 0.7 and 2.2 units (Figure 4e).

Both *AMP* and ΔII show a clear dependency on magnitude M_w and distance *R*. While the amplification factors of *PGA* and *PGA* (Figures 4a–4c) reach their maximum at the smallest magnitudes ($M_w \sim 5.0$) and closest distances ($R < 100$ km), we observe the opposite for instrumental intensity *II*, where the highest amplification (Figure 4d) occurs at large distances ($R > 300$ km). The largest increments ΔII are observed at large magnitudes ($M_w > 7.0$) and distances $R > 150$ km (Figure 4e).

The magnitude- and distance-dependence of *AMP* and ΔII can be explained as follows: the amplification of seismic wave amplitudes is controlled by the frequency content of the seismic bedrock input signal (corresponding to rock or VHR site condition), which depends on the characteristics of the earthquake source and of the seismic wave

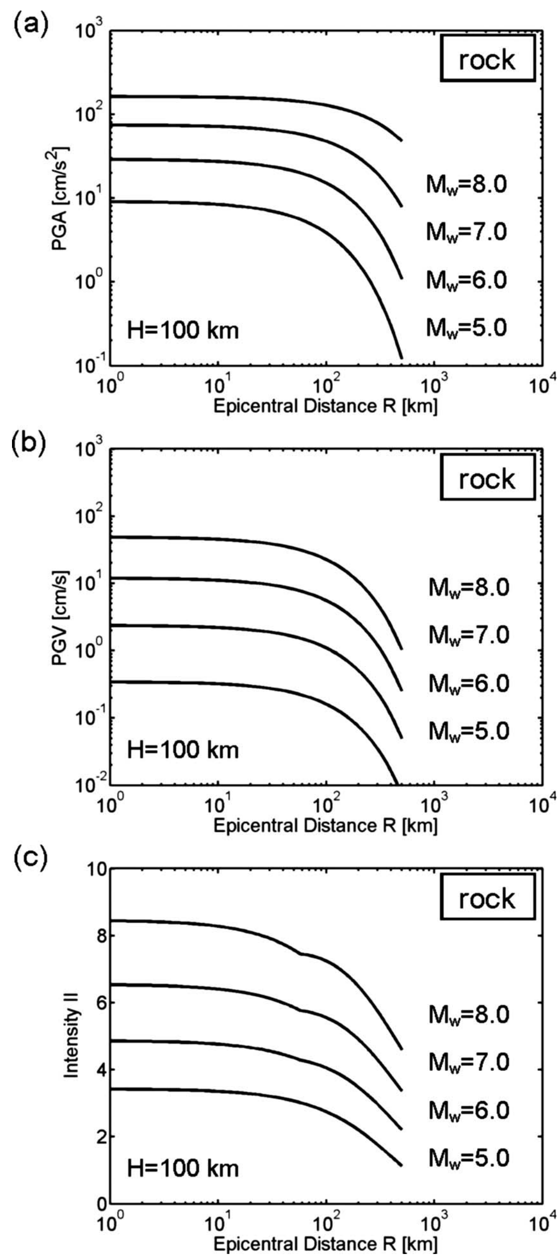

Figure 3. Empirical attenuation relations for rock condition in Romania for source depth H = 100 km: (a) *PGA*, (b) *PGV*, and (c) instrumental intensity (*II*).

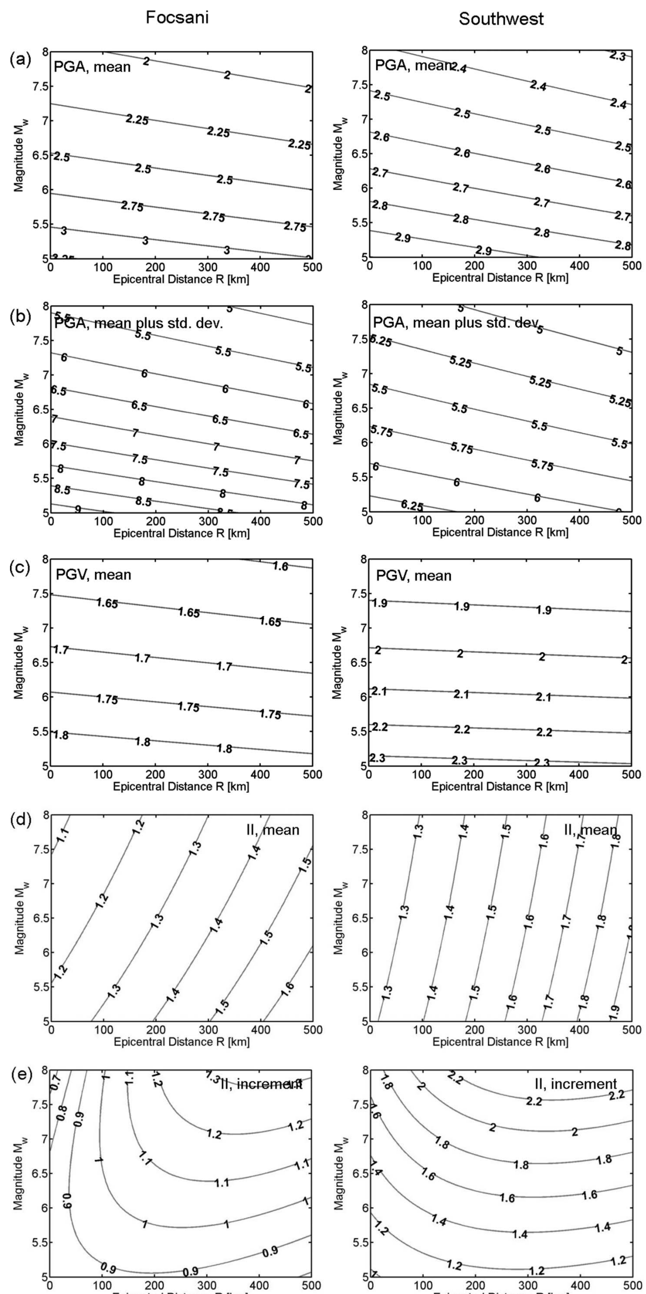

Figure 4. Amplification factors *AMP* and increments Δ*II* relative to rock as a function of magnitude M_w and epicentral distance *R* in the Focsani (left) and Southwest regions (right), for source depth *H*=100 km. The amplification values for (a) *PGA* (mean), (b) *PGA* (mean plus one standard deviation), (c) *PGV* (mean), and (d) instrumental intensity *II* (mean) are defined by the ground motion ratios in Equation 3a; (e) shows the intensity increment Δ*II* using Equation 3b.

propagation (such as M_w and R), and the corresponding spectral amplification in the subsurface layer (Figure 2). Large magnitude earthquakes ($M_w > 7.0$) usually produce long-period (<1 Hz) ground motions, while small magnitude earthquakes ($M_w = \sim 5.0$) mainly produce ground motions in the mid- to high-frequency (>2 Hz) range. With increasing travel distance R, seismic wave amplitudes decrease; high-frequency signals generally undergo a stronger attenuation than long-period motions. We can see in Figure 2 that strongest amplification in Romania usually occurs at frequencies between 2 and 15 Hz, i.e., in the mid- and high-frequency range. This means that high-frequency wave amplitudes of small magnitude earthquakes at close distances are stronger amplified than long-period waves of large magnitude earthquakes and events at large distances.

The broad-band site amplification (3 to 10 Hz, Figure 2) in the Southwest region generally leads to amplification factors *AMP* that are higher than those produced by the high-frequency site amplification (>10 Hz) in the Focsani region. This effect can be observed for both *PGA* and *PGV* (Figures 4a and 4c). When considering the possible extreme values of *PGA* using the mean plus one standard deviation of the generalized amplification functions, the Focsani region, however, exhibits much higher amplification values than the Southwest region (Figure 4b).

We can see from Figure 4d that the intensities of small and distant earthquakes are stronger amplified than the intensities of large and close events. This is because small earthquakes at far distances usually have small amplitudes that undergo a fairly strong amplification (Figures 4a–4c); thus we also have to expect large amplification of intensities. Large magnitude earthquakes at close distances, on the other hand, typically reveal large amplitudes that are only weakly amplified (Figures 4a–4c). Thus there are only small changes in amplitudes and thus in intensities.

The relationship between seismic wave amplitudes and instrumental intensity is of logarithmic nature (e.g., Wald et al. 1999). This means that intensity levels change faster for increasing small than for increasing large amplitudes. The largest intensity increments ΔII in Figure 4e are observed for strong earthquakes at moderate to large distances, i.e., opposite to what we have seen for the amplification factors in Figure 4d. The relationship between R, M_w, and ΔII becomes highly nonlinear.

SHAKE MAPS FOR VRANCEA EARTHQUAKES

We will now generate shake maps for Vrancea earthquakes using the prior described procedure: first, we estimate ground motions on a regular grid of phantom stations using the empirical attenuation relations for rock condition in Equation 1 and Equation 2; we then correct the available observational data to rock using the amplification factors *AMP* described in the previous section; we then interpolate all ground motion values onto a fine grid, and finally multiply each grid point with the corresponding *AMP* value.

We will demonstrate the shake map procedure for two Vrancea earthquakes: (1) a moderate-sized event of $M_w = 5.9$, which occurred on 27 October 2004 (45.78°N, 26.73°E, $H = 100$ km) with seismic recordings at 40 stations of the Romanian K2 strong motion network; and (2) the 1986 $M_w = 7.2$ Vrancea earthquake, which occurred on 30

August 1986 (45.52° N, 26.49° E, H=130 km). For this event there exist 20 records by SMA-1 sensors, operated by the Romanian National Institute for Earth Physics (NIEP), the National Institute for Building Research (INCERC), and GEOTEC Bucharest.

Figures 5a and 5b show the mean and the mean-plus-one standard deviation of estimated *PGA* levels for the 2004 Vrancea earthquake, while Figures 5c and 5d show the corresponding estimates for the 1986 event. Figures 5e and 5f depict the estimates of *PGV*, and Figures 6a and 6c the estimated instrumental intensities, *II*. For comparison, we show in Figure 6b the macroseismic intensities for the 2004 Vrancea earthquake obtained from the Did-you-Feel-It-web survey (Wald and Dewey 2005) with 245 responses in 50 cities (http://pasadena.wr.usgs.gov/shake/ous/STORE/Xqcck_04/ciim_display.html). Macroseismic intensities for the 1986 Vrancea earthquake are shown in Figure 6d (Radu et al. 1987).

Very large areas with predominant northeast-southwest orientations were affected by the two earthquakes (Figures 5 and 6), a typical characteristic of Vrancea events. Peak values of up to 260 cm/s^2 and 15 cm/s were observed southwest of the epicenter of the 2004 earthquake and up to 300 cm/s^2 and 30 cm/s northeast of the epicenter of the 1986 earthquake. Instrumental and macroseismic intensities ranged up to VII and VIII, respectively. There is a good agreement of estimated and observed ground shaking in both level and distribution.

For the comparison of estimated (instrumental) and macroseismic intensities, we plot in Figure 7 the corresponding residuals as a function of epicentral distance R. The standard deviations of residuals are ±0.6 intensity levels for both earthquakes. The largest error for the 2004 Vrancea earthquake (Figure 7a) is observed at a site 110 km southwest of its epicenter with a macroseismic intensity of VII, while the estimated intensity is only IV (Figure 6b). Note from Figure 6a that also the intensity level determined from the seismic record of a near-by K2 station is surprisingly high for a M_w=5.9 earthquake at this distance. Other stations in this area, however, reveal much smaller intensity levels, suggesting that the effect might be caused by spatially very limited site conditions. We observe a much larger scatter in the residuals of the 1986 Vrancea earthquake (Figure 7b), mainly at distances $R>200$ km. Note, however, that the study of residuals might be misleading to some extent; macroseismic intensities are *integer* values, i.e., positive natural numbers, while instrumental intensities, *II*, are *decimal* values, i.e., they have a higher precision.

COMPARISON WITH WALD AND ALLEN (2007)

Finally, we compare our results with outcomes of the empirical relationship between topographic slope and site amplification as recently proposed by Wald and Allen (2007). This approach has the clear strength of providing a tool for uniform site amplification mapping all over the world, as required, for example, by the Prompt Assessment of Global Earthquakes for Response (PAGER) program (Wald et al. 2006).

We download for Romania V_{S30} values estimated from topographic slopes using 30 arc-sec global topography data (SRTM30; Farr and Kobrick 2000) from the V_{S30} Global Map Server (http://earthquake.usgs.gov/research/hazmaps/interactive/vs30/). We

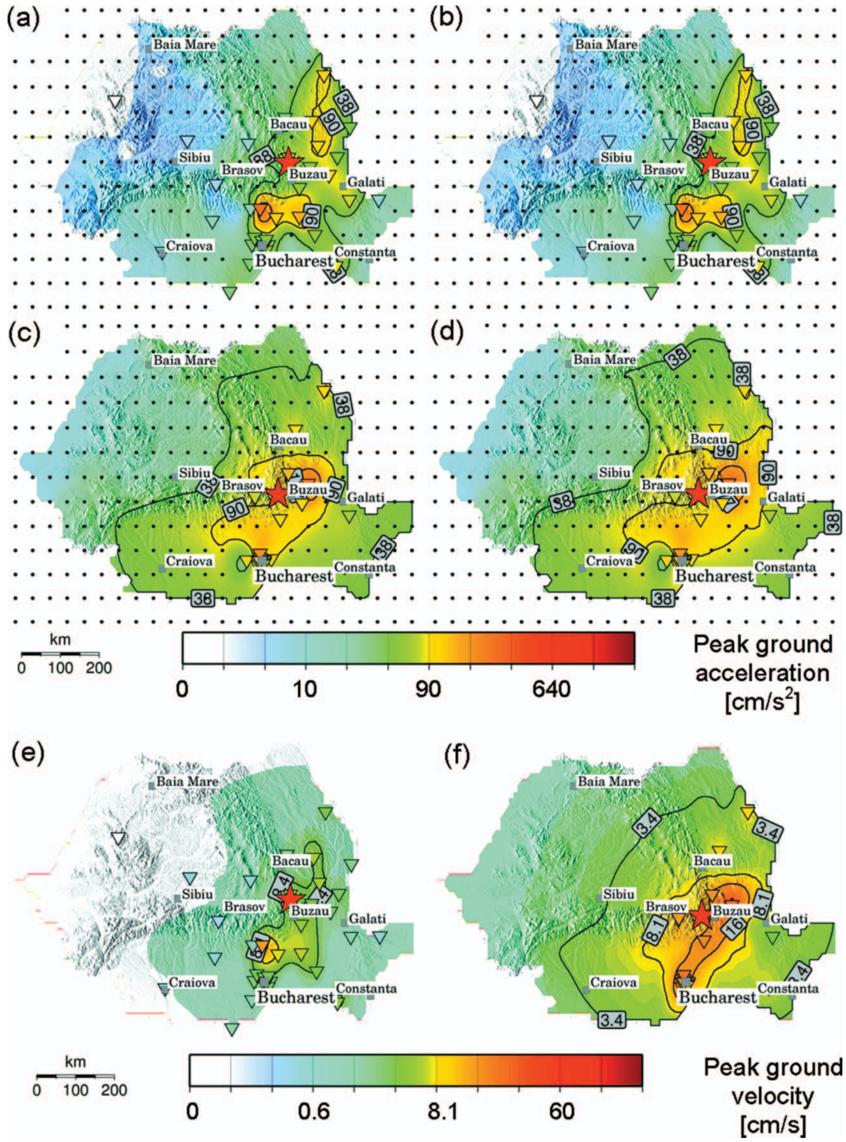

Figure 5. Shake maps for the 2004 $M_w=5.9$ and the 1986 $M_w=7.2$ Vrancea earthquakes. (a) and (b) show the mean and the mean plus one standard deviation estimate of *PGA* for the 2004 earthquake, (c) and (d) the corresponding estimates for the 1986 event. (e) and (f) show the mean *PGV* estimate for the two earthquakes. Triangles mark locations of recording K2 stations (for the 2004 Vrancea earthquake) and SMA-1 sensors (for the 1986 Vrancea earthquake), stars show locations of the epicenters. Phantom sites are shown by dots. Very large areas with a predominant northeast-southwest orientation were affected by the two earthquakes—a typical characteristic of Vrancea earthquakes. Seismic waves in the Transylvanian basin undergo very strong attenuation.

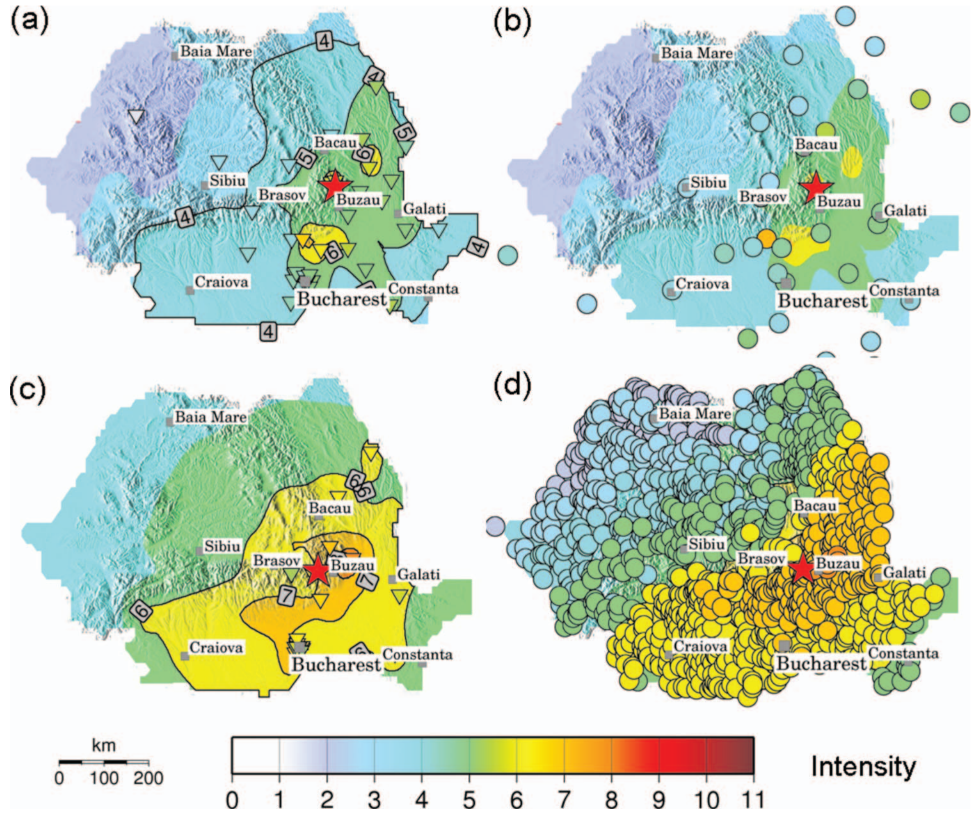

Figure 6. Shake maps for the 2004 M_w=5.9 and the 1986 M_w=7.2 Vrancea earthquakes. (a) and (c) show the estimated instrumental intensities *II* of the two events; (b) and (d) show the macroseismic intensities determined from questionnaires (Wald and Dewey 2005, Radu et al. 1987). Triangles mark locations of recording K2 stations (for the 2004 Vrancea earthquake) and SMA-1 sensors (for the 1986 Vrancea earthquake). Circles show sites where human descriptions of (macro-) intensities are available.

apply amplitude-dependent amplification factors as a function of V_{S30} (Borcherdt 1994) with NEHRP class B/C as a reference (Wills and Clahan 2006); this reference agrees well with the attenuation relation for rock condition in Equation 1 (Sokolov et al. 2008).

Figure 8 shows shake maps calculated from the two approaches for site amplification mapping, on the left using the topographic slope (Wald and Allen 2007), on the right using the seismological method developed in this paper. Figures 8a and 8b show shake maps for *PGA* for the 2004 and the 1986 Vrancea earthquakes, Figures 8c and 8d the corresponding *PGV* maps. All shake maps are calculated from the empirical attenuation relation for rock condition in Equation 1 together with the respective amplification factors obtained from the two methods. For simplicity we omit the recorded ground motions as were displayed in Figure 5.

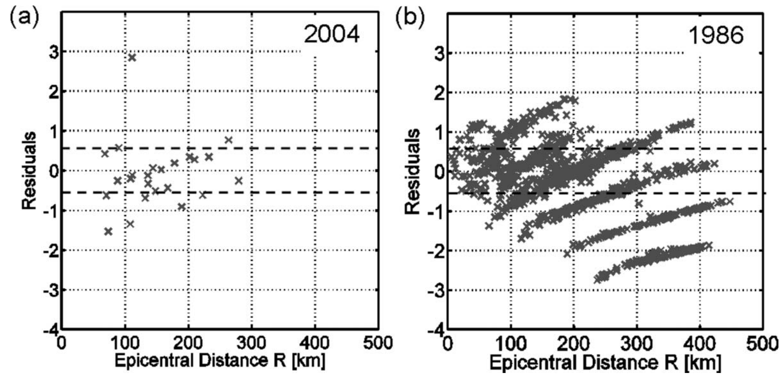

Figure 7. Residuals of estimated instrumental intensities *II* and macroseismic intensities determined from questionnaires after the (a) 2004 $M_w = 5.9$ and the (b) 1986 $M_w = 7.2$ Vrancea earthquakes. The dashed lines show one standard deviation of the residuals.

The overall picture of the shake maps in Figure 8 is quite similar: *PGA* values for the 2004 event go up to 100 cm/s^2 and up to 200 cm/s^2 for the 1986 Vrancea earthquake; the *PGV* values go up to 3 cm/s and up to 10 cm/s, respectively. Note, however, that the method proposed by Wald and Allen (2007) tends to overestimate ground shaking in the Transylvanian basin, with *PGA* values of 10 to 20 cm/s^2 (2004) and 50 cm/s^2 (1986) and *PGV* values of up to 1 cm/s (2004) and 4.5 cm/s (1986). The seismological approach, in contrast, predicts *PGA* values of $<$3 cm/s^2 (2004) and $<$20 cm/s^2 (1986), and *PGV* values of $\sim$0 cm (2004) and $<$3 cm (1986). It has been repeatedly observed during past Vrancea earthquakes that seismic waves in the Transylvanian basin undergo a surprising strong attenuation (e.g., Popa et al. 2005, Radulian et al. 2006). Oth et al. (2008) explain this attenuation by extremely low *Q* values in the mantle. As a matter of principle, the topographic approach by Wald and Allen (2007) cannot reflect these mantle anomalies and thus overestimates ground shaking in Transylvania. On the other hand, the usage of the Wald and Allen (2007) method leads to an underestimation of ground motions to the east and south of Vrancea. For example, the approach predicts $PGA < 60$ cm/s^2 (2004) and $PGA < 140$ cm/s^2 (1986), while our seismological approach predicts *PGA* values of around 90 cm/s^2 (2004) and up to 200 cm/s^2 (1986).

DISCUSSIONS AND CONCLUSIONS

Shake maps, such as the well-known Californian ShakeMap (Wald et al. 1999), usually require a geology-based classification of seismic site effects for the assignment of amplification factors of seismic ground motion at a grid of phantom sites. Using the example of Romania, we developed in this paper an alternative shake map methodology that does not require relationships between surface geology and site amplification. Instead, our method uses region-specific (azimuth-dependent) attenuation relations and amplification functions determined from seismological information gathered during previous Vrancea earthquakes (Sokolov et al. 2008).

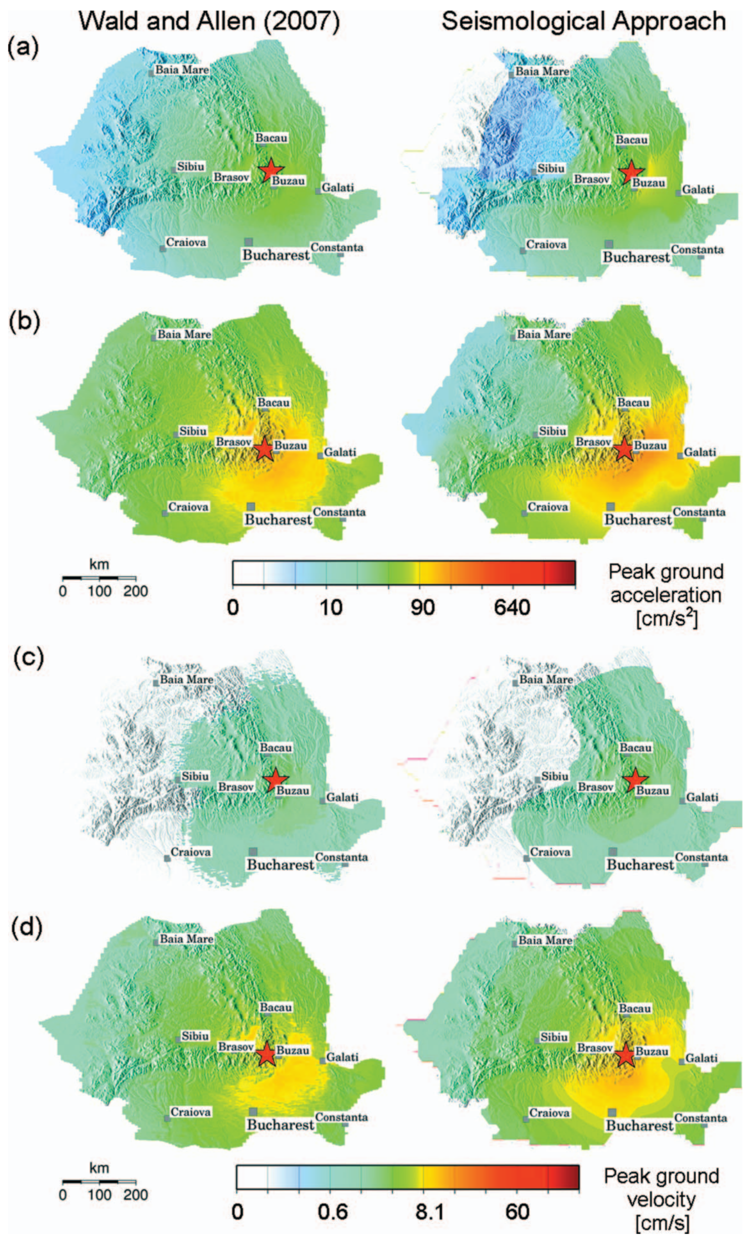

Figure 8. Comparison of shake maps for the 2004 M_w=5.9 and the 1986 M_w=7.2 Vrancea earthquakes computed from amplification factors derived from topographic slope (Wald and Allen 2007) (left) and the seismological approach developed in this paper. (a) and (b) show *PGA*, (c) and (d) *PGV*. While the overall picture for the two approaches is quite similar, the method proposed by Wald and Allen (2007) tends to overestimate ground shaking in the Transylvanian basin, and underestimates motions East and South from Vrancea.

The strength of a seismologically based shake map approach is that it allows utilizing any kind of weak, moderate, and strong motion observations of past earthquakes. These include in the case of Romania several weak motion observations, a few records of strong earthquakes (1986 and 1990), and intensity maps for four strong events (1944, 1977, 1986, and 1990). Sokolov et al. (2005) used these data for the development of spectral amplification functions at various sites in southeastern Romania. We use attenuation relations derived from these spectral models (Sokolov et al. 2008) to characterize the site amplification in eight characteristic regions in Romania.

As a matter of principle, attenuation relations predict only the general features of ground motion, not peculiarities of special earthquakes. In many cases (and this is even more true shortly after a strong earthquake, i.e., when shake maps are mostly required), source parameters, and in particular slip distributions, are widely unknown. For the development of attenuation relations for Vrancea earthquakes, Sokolov et al. (2008) therefore used generalized source parameters (seismic moment and stress parameter) and simple models of source scaling and attenuation. We thus assume that the obtained region-specific (azimuth-dependent) attenuation relations do not give only a reflection of site effects in the different regions but that they are also affected by the peculiarities of source characteristics of Vrancea earthquakes, including, for example, patterns of seismic S-wave radiation.

In a systematic study, we determined in this paper region-specific magnitude- and distance-dependent amplification factors for Vrancea earthquakes, including peak ground acceleration (*PGA*), peak ground velocity (*PGV*), and instrumental intensity *II* (Figure 4). Our findings reveal general features of seismic ground motions near the earthquake source: depending on the amplitude of the seismic input signal, the severity of shaking in terms of instrumental intensity *II* and *PGA* may reveal a reverse picture.

In general, shake maps show a dependency on parameters used for the interpolation of ground motions at recording stations and phantom sites. The specification of these parameters is not trivial. In this study, we arranged the phantom stations on a regular grid of 45 km spacing covering the Romanian territory. Prior to the interpolation, we removed sites within a 35 km radius around each recording station. The California ShakeMap, in comparison, uses 30 km spacing and removes phantom sites closer than 30 km from recording stations (Wald et al. 1999). The spacing of phantom sites mainly depends on the station density. Stations of the Romanian K2 network in southeastern Romania have a spacing of 50 km to 100 km; in some areas distances between adjacent sensors are much larger (Bonjer et al. 2000). If the grid of phantom sites is denser than the network of recording ground motion sensors, these sites might become assigned too high a weight in the interpolated shake maps, which is not desired. We think that the spacing of phantom sites should be in the same order like the average spacing of recording stations in the shake map area. The removal of phantom sites close to the recording stations depends on the spatial correlation of seismic ground motions (Boore et al. 2003, Quitoriano et al. 2007). For future application, more systematic studies for the determination of parameters for optimum interpolation for shake maps in Romania and elsewhere are required.

We compared our results with outcomes from the empirical topographic slope and amplification approach by Wald and Allen (2007). While the overall picture of shake maps generated by the two approaches is similar, the method proposed by Wald and Allen (2007) tends to overestimate ground shaking in the Transylvanian basin and underestimates motions East and South from Vrancea.

Our work demonstrates that there is no need to wait for the decades that are necessary to establish a reliable strong motion database before a shake map with an intelligent interpolation of observed ground motion parameters can be delivered. For future studies of shake maps in Romania, we propose to include site-specific correction of the terms of the generalized amplification functions and empirical attenuation relations. Besides, in the case of very strong earthquakes, source finiteness needs to be taken into account.

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